

Optical variability of the LMC supersoft source RX J0513.9-6951 from MACHO Project photometry

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ABSTRACT

Using the exceptional monitoring capabilities of the MACHO project we present here the optical history of the LMC supersoft source (SSS) RX J0513.9-6951, for a continuous 3 year period. Recurring low states, in which the optical brightness drops by up to a magnitude, are observed at quasi-regular intervals. This provides a crucial insight into the nature of the SSS and, in particular, a chance to investigate the poorly understood behaviour of their accretion discs. Analysis of the high state data reveals a small modulation of semi-amplitude ~ 0.02 magnitudes at $P=0.76278\pm0.00005$ days, a period which is consistent with the current “best” suggested spectroscopic value.

Key words: accretion, accretion discs – binaries: close – binaries: spectroscopic – X-rays: stars – Stars: individual: RX J0513.9-6951

1 INTRODUCTION

ROSAT observations have considerably enlarged the new class of high luminosity X-ray objects, the so-called “supersoft sources” (SSSs) characterised by their EUV temperatures (Trümper 1992). SSSs were first detected in the Large Magellanic Cloud in 1979-1980 with the *Einstein* X-ray Observatory (Long, Helfand & Grabelsky, 1981). Until recently, little progress had been made in determining the exact nature of these elusive systems, the high level of X-ray absorption rendering them undetectable in the Galactic plane. Most currently known SSS are therefore extragalactic and, as such, they are optically faint.

The current inventory of supersoft objects (Hasinger 1994; Cowley et al. 1996; Kahabka & Trümper 1996) is of the order of 11 in the Magellanic Clouds, 15 in M31 and 7 Galac-

tic sources, with candidates existing also in M101, NGC253 and M33. It appears now, through *ROSAT* observations, that the SSS do not form a strictly homogeneous class, some having been identified with a planetary nebula nucleus (Wang 1991), a PG 1159 star (Cowley et al. 1995) and symbiotic systems (e. g. Hasinger 1994). However, the bolometric luminosities of these objects ($L_{\text{bol}} \sim 10^{37} \text{ erg s}^{-1}$) are typically an order of magnitude less than the original *Einstein* sources, CAL 83 and CAL 87.

Among the *ROSAT* discoveries are several systems, including RX J0513.9-6951 (hereafter RX J0513-69) which show the hallmarks of the original LMC SSS. Typically, $L_{\text{bol}} \sim 10^{38} \text{ erg s}^{-1}$ and $T_{\text{bb}} \sim 30 \text{ eV}$. Spectroscopic studies (Smale et al. 1988; Pakull et al. 1988) readily identified them as low mass X-ray binaries (LMXBs), yet the nature

of the compact object and the source of the soft emission proved elusive. Previously, X-rays of such low energy had only been observed in certain types of cataclysmic variables (CVs), but these accreting white dwarf binary systems are typically about a million times fainter than the SSS (see e.g. Warner 1995).

In 1990, CAL 87 was proposed to be a black hole binary, on the basis of a radial velocity analysis (Cowley et al. 1990). The following year, a paper appeared advocating the scenario of a neutron star accretor, shrouded in a dense cocoon of ionised matter (Greiner, Hasinger & Kahabka 1991). However, neither model seemed to provide a natural explanation for the extremely soft X-ray emission.

The most significant progress occurred when van den Heuvel et al. (1992) proposed a model for the SSS which involved a white dwarf primary undergoing accretion at a rate $\gtrsim 10^{-7} M_{\odot} \text{ yr}^{-1}$. It was shown that steady nuclear burning on the white dwarf surface could produce the extremely soft X-ray emission at the required luminosities. However, such high accretion rates require a donor star more massive than the white dwarf, in order to sustain thermally unstable mass transfer.

We have therefore undertaken a programme of optical spectroscopy and photometry, to test the predictions of this model. In particular, we focus on the LMC group, since the accurately known distance of these high luminosity SSSs is a vital key in understanding their nature. We present here the results of long-term optical photometry of the transient LMC source, RX J0513-69, which was discovered in the ROSAT All Sky Survey (Schaeidt, Hasinger & Trümper 1993). Remarkably, these observations were acquired as a serendipitous by-product of the MACHO project (Alcock et al. 1995a), owing to the location of RX J0513-69 in a frequently monitored field. We are thus afforded an unprecedented opportunity to study the long term behaviour of this source which, at $V \sim 16-17$, would normally be impossible.

2 OBSERVATIONS

The relative magnitude of RX J0513-69 for the period 1992 August 22 – 1995 November 27 is presented in Fig. 1. The observations were made using the 1.27-m telescope at Mount Stromlo Observatory, Australia. A dichroic beamsplitter and filters provide simultaneous CCD photometry in two passbands, a ‘red’ band ($\sim 6300-7600 \text{ \AA}$) and a ‘blue’ band ($\sim 4500-6300 \text{ \AA}$). However, we show here only the observations taken through the latter filter, which is approximately equivalent to the Johnson V passband, since the red light curve is not appreciably different. The vertical dotted lines indicate our working definition of the ‘high’ and ‘low’ state sections, as used in the power spectrum analysis.

The images were reduced with the standard MACHO photometry code SoDoPHOT, based on point-spread function fitting and differential photometry relative to bright neighbouring stars. One-sigma error bars are shown, which are usually smaller than the data points ($\approx 0.02 \text{ mag}$); for some observations with very poor seeing or transparency, the errors rise to $\sim 0.1 \text{ mag}$. Further details of the instrumental set-up and data processing may be found in Alcock et al. 1995b, Marshall et al. 1994 and Stubbs et al. 1993.

The absolute calibration of the MACHO fields and

transformation to standard passbands is not yet complete, thus the measurements are plotted differentially relative to the observed median. A preliminary estimate indicates that $\Delta m = 0$ corresponds to $V \approx 16.3$ and $V - R \approx 0.08$, with systematic uncertainties around 0.2 and 0.1 mag respectively. The final calibration will greatly reduce these uncertainties, but they do not affect the differential measurements presented here.

The system exhibits pronounced optical variability, with the most dramatic changes occurring on timescales of $\sim 100-200 \text{ d}$. The brightness typically drops by $\sim 0.8-1.0 \text{ mag}$ in only $\sim 10 \text{ d}$, after which the light curve maintains a low level for $\sim 30 \text{ d}$. It should be noted, however, that following the initial drop, the system usually brightens by $0.3-0.4 \text{ mag}$ in the first $\sim 8 \text{ d}$, and maintains this plateau level before making the rapid upward transition back to the high state. This pattern of variability is less obvious in the low state at day number ~ 1540 , in which the system appears to undergo a minor outburst, rather than exhibiting the step-like behaviour.

The first and final low states of Fig. 1 exhibit a somewhat more gradual decrease in magnitude than the others, taking around a week longer to drop to the faintest level. The overall drop is also relatively smaller by $\geq 0.1 \text{ mag}$. The magnitude at which the system starts to enter a low state appears essentially constant ($\Delta m = 0$), except perhaps for the faint episode at day number ~ 900 , which begins at $\Delta m = -0.2$. During the high states, the brightness appears to show a roughly linear fading, amounting to $\sim 0.2 \text{ mag}$ in total, independent of the interval of time between the low states. We note that it is probable, both from the recurrence times of the low states and from the decline of the light curve before day ~ 1320 , that a low state was missed in the period $\sim 1320-1370$, during which there is a gap in the monitoring. Indeed, spectroscopic observations obtained in December 1992 by Reinsch (in preparation) strongly suggest that RX J0513-69 was in an optical low state during this time.

3 PERIOD ANALYSIS

We analysed the high state sections, as defined by the vertical dotted lines in Fig. 1, for any periodic behaviour. Due to the fact that the intrinsic variability of RX J0513-69 of up to $\sim 0.3 \text{ mag}$ in the ‘flat’ regions of the light curve can mask orbital modulations, we detrended each high state section separately, by subtracting a linear fit, before performing a power spectrum analysis on the combined dataset. The resulting Lomb-Scargle (Lomb 1976; Scargle 1982) periodogram is shown in Fig. 2, for a frequency space of $0.1-10 \text{ cycles d}^{-1}$, with a resolution of $0.001 \text{ cycles d}^{-1}$. We see a dominant peak at $P = 0.76278 \pm 0.00005 \text{ d}$, with lesser power at 3.22 d and 1.45 d . However, the former of these secondary peaks is almost certainly a one-day alias, having a frequency of 1 cycle d^{-1} less than that of the 0.76278 d period. Furthermore, we checked the significance of the peaks by analysing the power spectra of randomly generated datasets, using the sampling intervals of the real data. Our Monte Carlo simulations reveal that the 1.45 d peak is significant at only the $\sim 1.6\sigma$ level. However, the power at $P = 0.76278 \pm 0.00005 \text{ d}$ corresponds to a 5σ detection, leading us to present this as

the true orbital period. Independent spectroscopic studies (Crampton et al. 1996) are consistent with this result, having revealed a ‘best’ period of $P \approx 0.76$ d.

The high state data were folded on $P = 0.76278$ d to examine the form of the orbital modulation. We find that the data are well fitted by a sinusoid of semi-amplitude 0.0213 ± 0.0009 mag, suggesting a low inclination. This phase-averaged, folded light curve is shown in Fig. 3. We derive an ephemeris of $T_o = \text{JD } 2448857.832(5) + 0.76278(5)E$, where T_o is the time of maximum optical brightness, and E is an integer.

4 DISCUSSION

Recently, Crampton et al. (1996) reported variations of only ~ 0.3 mag, noting that the optical counterpart, identified as HV 5682, has historically shown variations of up to ~ 1 mag. Placing these observations in the context of the MACHO light curve, it is clear that both findings are consistent with the data presented here. In the more usual optical high states, variations of up to ~ 0.3 mag commonly occur on timescales of days (see Fig. 1). Clearly, the more dramatic variation of ~ 1 mag can be identified with transitions to the rather more infrequent low states, detection of which requires extended monitoring of the type reported here.

The optical luminosity in this system is expected to be dominated by the EUV/soft X-ray heated accretion disc, which has an absolute visual magnitude $M_V \approx -2$ in the high state, at the high extreme of LMXBs in general (van Paradijs & McClintock 1995). Indeed, it is remarkable that *all* the LMC LMXBs are optically so luminous. This may be compared to typical values of $M_V = +4$ to $+7$ for CVs (van Paradijs 1983). Even if we apply the Warner (1987) empirical relation:

$$M_V^{\text{disk}} = 5.74 - 0.259 P_{\text{orb}}(\text{hr}) \quad (P_{\text{orb}} \lesssim 15 \text{ hr}) \quad (1)$$

for the brightness of dwarf novae discs at maximum, using $P_{\text{orb}} \approx 18$ hr, we obtain $M_V = +1.1$, substantially fainter than observed for RX J0513-69. This suggests that there is an additional source of optical luminosity in the system, consistent with the van den Heuvel et al. (1992) scenario of a white dwarf undergoing surface nuclear burning.

Using our orbital period of $P = 0.76278$ d, we may calculate the mean density, $\bar{\rho}$, of the companion star under the assumption that it fills its Roche lobe. We combine Kepler’s third law and the Eggleton (1983) relation for a Roche-lobe filling star:

$$\frac{R_{L_2}}{a} = \frac{0.49q^{-2/3}}{0.6q^{-2/3} + \ln(1 + q^{-1/3})}, \quad (2)$$

where R_{L_2} is the radius of a sphere with the same volume as the secondary Roche lobe, a is the binary separation, and q is the binary mass ratio ($\equiv M_{\text{compact}}/M_{\text{secondary}}$) to obtain:

$$\bar{\rho} = \frac{0.161}{P^2(1+q)} (0.6 + q^{2/3} \ln(1 + q^{-1/3}))^3 \text{ g cm}^{-3}, \quad (3)$$

where P is in days. For values of $q \lesssim 1$, as required by the van den Heuvel et al. 1992 model, the implied mean density is $\sim 0.2 - 0.3 \text{ g cm}^{-3}$. This is consistent with that of a $\sim 2.5 - 3.0 M_{\odot}$ main sequence star (of spectral type $\sim A0$). The light from such a star would still be dominated by

the accretion disk/compact object luminosity, since for an LMC distance modulus of 18.5 (e. g. Panagia et al. 1991) its apparent magnitude would be ~ 19 , significantly fainter than the observed brightness of RX J0513-69 of $V \sim 17$.

5 SUMMARY

In conclusion, we have used the remarkable monitoring capability available as a by-product of the MACHO project to observe, for the first time, the long term optical behaviour of the recurrent SSS RX J0513-69. We see marked high and low states in the optical. The relation of these optical variations to the X-ray behaviour is currently under investigation (Southwell et al. 1996). Indeed, ROSAT has so far discovered three X-ray on states for this transient source, making it the first SSS to exhibit recurrent outbursts (Hasinger 1994; Schaeidt, in preparation). We derive an orbital period of $P = 0.76278 \pm 0.00005$ d, consistent with independent spectroscopic findings. Such a binary system allows solutions for the nature of the secondary star that are consistent with the van den Heuvel et al. (1992) model of unstable mass transfer onto a white dwarf. Given the small photometric orbital modulation (~ 0.02 mag semi-amplitude) and the extreme optical variability of this source, we strongly urge further spectroscopic observations.

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Figure 1. The optical light curve of RX J0513–69 from 639 observations taken during the MACHO project. The relative magnitude is shown for the ‘blue’ filter, which is approximately equivalent to the Johnson *V* passband. Note the quasi-regular magnitude drops of ~ 1 mag. The day number is JD–2448000. The vertical dotted lines indicate our working definition of the ‘high’ and ‘low’ state sections, as used in the power spectrum analysis.

Figure 2. The Lomb-Scargle periodogram of RX J0513-69 MACHO time series data, excluding the low states. The strongest peak is at 0.76278 ± 0.00005 d.

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Figure 3. The light curve of RX J0513-69, folded on a period of 0.76278 d. The data have been averaged into 30 phase bins, and are fitted with a sinusoid of amplitude 0.0213 mag. Two cycles are plotted for clarity.





